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IRRIGATED FESCUE GRASS ET COMPARED WITH CALCULATED REFERENCE GRASS ET

T.A. Howell, S.R. Evett, A.D. Schneider, D.A. Dusek, and K.S. Copeland *

ABSTRACT

Cool-season, short, and well-watered grass is the world-wide standard reference for crop evapotranspiration (ET) research and practice. Fescue grass (*Festuca arundinacea* Schreb.) was grown at Bushland, TX since 1995, and its water use measured with a monolithic, weighing lysimeter. The grass was mowed (to 0.11 m) and irrigated frequently and managed for vigorous growth. It was irrigated with a subsurface drip irrigation (SDI) system. Data were analyzed for the period 1 July 1995 through December 1999 that included a wide diversity in climatic regimes. Several grass reference ET models including FAO-56 Penman-Monteith (PM), ASCE PM, FAO-24 Penman, Kimberly-96 Penman, SCS-93 PM, Penman-48, and the Hargreaves-Samani equations all for grass; the ASCE PM and Kimberly-82 Penman equations for alfalfa (*Medicago sativa* L.); and the general Priestley-Taylor equation for non-advected conditions were evaluated and contrasted with the daily grass ET measurements. Measured fescue daily ET rates exceeded 10 mm d^{-1} occasionally. The FAO-56 and ASCE Penman Monteith equations tended to over-estimate during spring and fall and under-estimate during summer and especially on high ET days (> 8 mm d^{-1}). The older Penman formula ET correlated well to the measured daily data. The Hargreaves-Samani and Priestley-Taylor equations substantially under estimated grass ET in this environment.

KEYWORDS: Alfalfa, Climate, Crop coefficient, Evapotranspiration, Grass, Lysimeter, Net radiation, Water use

INTRODUCTION

Evapotranspiration (ET) from a well-watered grass has long been used as a reference value for estimating crop consumptive use. Jensen (1968) defined the crop coefficient, K_c as

$$K_c = E_t / E_o \tag{1}$$

where E_t was the crop ET, and E_o was the "potential" or upper limit ET expected and defined E_o as

> *"....the upper limit of evapotranspiration that occurs with a well-watered agricultural crop that has an aerodynamically rough surface such as alfalfa with 30-50 cm of top growth."* ...(Jensen, 1968)

And he further clarified that the "fetch" needed was at least 30 m and specifically included effects of regional advection or the "oasis" effect within his characterization of E_o. Doorenbos and Pruitt (1975 and 1977) further developed this concept for many crops for the Food and

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* Terry A. Howell, Research Leader (Agricultural Engineer); Steve R. Evett, Soil Scientist; Arland D. Schneider, Agricultural Engineer; Donald A. Dusek, Agronomist; and Karen Copeland, Soil Scientist, USDA-ARS, Conservation and Production Research Laboratory, P.O. Drawer 10, Bushland, TX 79012. (Email:tahowell@ag.gov).

Agricultural Organization (FAO) of the United Nations as a method applicable world-wide, but they used a different basis for the "reference crop evapotranspiration" (one of the first mentions of the reference ET concept to our knowledge). They defined the crop coefficient similarly, but used the symbol kc (for K_c as in Eq. 1), and they specified the reference ET_o (for E_o in Eq. 1) as

> *".....the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water."* ...(Doorenbos and Pruitt, 1977)

Burman et al. (1980 a and b) further developed the concept of using either of two crops, grass or alfalfa (*Medicago sativa* L.), as the "reference crops." In theory, any crop could be a reference crop although alfalfa and grass have distinct advantages. All of these works intended that the "potential ET" or "reference ET" would be a calculated value from any one of many methods based on local climate data. Many of the K_c values developed at Davis, CA, by Pruitt (Doorenbos and Pruitt, 1977) were based on simultaneous measurements of grass reference ET and crop ET with two lysimeters (one was a weighing lysimeter and the other was a floating type) (Pruitt et al., 1972). Few direct comparisons of reference crop ET for alfalfa and grass exist to our knowledge, although ET from both reference crops has been measured at Kimberly, ID, by Wright (1982 and 1996) but not simultaneously. All of these definitions of reference ET lead back to Penman's work (Penman, 1948, 1956, 1963) that defined "potential evaporation" as

> *"...the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water."* ...(Penman, 1956)

Businger (1956) and van Bavel (1966) attempted to clarify concepts of "potential evaporation" and inserted an adiabatic wind speed profile characterization for the empirical wind function employed in the Penman combination type equations. But these more theoretical "wind functions" have been reported to over predict potential evaporation in windy and dry humidity conditions (Rosenberg, 1969).

All of the Penman combination type equations assume indirectly that the surface resistance is zero and that the aerodynamic resistance is included within the wind function itself. Covey (1959), Rijtema (1965), and Monteith (1965) characterized this surface resistance in what now has become known as the "single layer" or "big leaf" model to better account for crop surface effects on aerodynamic properties and to include a surface resistance to the evaporation Penman combination equation. This equation has become widely known as the Penman-Monteith (PM) equation (Monteith, 1965) and the ASCE version (Jensen et al., 1990) is given as

$$ET_c = \frac{\Delta\,(R_n - G) + 86.4\,\rho\,C_p\,(e_s - e_a)/r_a}{\lambda\,[\Delta + \gamma\,(1 + r_s/r_a)]} \tag{2}$$

where ET_c is the ET of the crop in mm d^{-1}, Δ is the slope of the saturation vapor pressure versus temperature curve in kPa $°C^{-1}$, R_n is net radiation in MJ m^{-2} d^{-1}, G is sensible heat flux into the soil in MJ m^{-2} d^{-1}, ρ is air density in kg m^{-3}, C_p is specific heat of moist air [1.013 kJ kg^{-1} $°C^{-1}$], e_s is the mean saturated vapor pressure in kPa, e_a is mean ambient vapor pressure in kPa, r_a is the aerodynamic resistance in s m^{-1}, r_s is the bulk surface resistance to evaporation in s m^{-1}, λ is the latent heat of vaporization in MJ kg^{-1}, γ is the psychrometric constant in kPa $°C^{-1}$, and the 86.4 is a time conversion constant. The resistance factors are explicitly defined for the crop of interest, and all other factors are measured (or computed) over or below the crop of interest. Jensen et al. (1990) proposed standardizing reference ET computations for grass at constant 0.12-m height and for alfalfa at a constant 0.50-m height based on Allen (1986) and Allen et al. (1989). They recommended using the PM combination equation for weekly, daily, or shorter periods with their formulated resistance factors and procedures for estimating both R_n and G. They discussed problems with non representative climate data and recommended that R_n and G procedures may need to be tested in environments dissimilar to the ones they had used for developing their recommended coefficients. Readers are cautioned that measuring R_n and G are in themselves no simple matter and any measurements of either R_n or G may contain significant instrument biases (Fritschen and Gay, 1979; or Allen et al., 1994b). Of course, errors in measuring G are insignificant on a longer time scale (greater than one day) in regards to ET and the energy balance of irrigated crops. Wright (1996) noted that the alfalfa R_n methods previously developed for Kimberly, ID, (Wright, 1982) worked well for clipped fescue grass, except for October, but only analyzed data for the April through October period. He indicated that a modified R_n methodology may be needed for grass.

The Penman-Monteith method outlined by Allen (1986) for grass was used by Martin and Gilley (1993) for developing the latest ET methods for USDA-NRCS (formerly the USDA-SCS, Soil Conservation Service). The only noticeable difference was that they used the grass albedo estimation method from Dong et al. (1992) and estimated net long-wave radiation using methods for alfalfa from Wright (1982).

Allen et al. (1994 a and b) and Allen et al. (1998) provided the recommended International Commission on Irrigation and Drainage (ICID) and the Food and Agriculture Organization of the United Nations (FAO) methodologies for estimating reference crop ET for grass (called ET_o hereafter). Their definitions of the "hypothetical" grass surface conditions were the following:

height	0.12 m
surface resistance	70 s m^{-1}
albedo	0.23
grass species	cool season type like perennial ryegrass (*Lolium perenne* L.) or tall fescue (*Festuca arundinacea* Schreb.)

Although not explicitly stated, they assumed an emissivity for the grass of 0.98. Further they used the common working assumption that Δ could be estimated at the mean ambient air temperature (van Bavel, 1966). Allen et al. (1998) made further simplifications for λ (constant at 2.451 MJ kg^{-1}) and ρ that may be unnecessary in this age of powerful personal computers, in our opinion, but these simplifications don't introduce any significant compromise in accuracy (at least for our conditions) resulting in the simplified FAO-56 PM ET_o equation given as

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{(T + 273)}\,u_2(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \qquad (3)$$

where T is mean daily air temperature in °C and u_2 is mean daily 2-m wind speed in m s^{-1}. The constants of 900 and 0.34 apply strictly to temperature, relative humidity, and wind measured at 2 m. Allen et al. (1994a) compared computed reference grass ET using the ICID-PM (which is practically the same as the FAO-56 PM) equation with lysimeter-measured grass ET at Davis, CA for a five-year period (1965 through 1969). For these daily data, the ICID-PM equation performed considerably better than the FAO-24 Penman equation (Doorenbos and Pruitt, 1977), but only slightly better than the 1963 Penman equation (Penman, 1963). A variable r_s characterization based on solar radiation and/or vapor pressure deficit (VPD) did not improve the ICID-PM results. Todorovic (1999) using a variable r_s function found a daytime r_s value of 40 s m^{-1} at Davis, CA, but he reported little differences on calculated hourly ET using the variable r_s compared with a constant of 70 s m^{-1}. Allen et al. (1994b) reported hourly comparisons for a tall clipped fescue grass at Logan, UT, for 3 days in August in 1990. The ICID-PM equation slightly underestimated the measured grass ET by 3-4% for the whole day, but when the r_a value was corrected using a gradient Richardson number, which requires at least two levels of air temperature and wind speed measurements, better agreement was observed between the hourly measured and computed ET rates, particularly if R_n was computed as well. The daily summed hourly ET rates were reportedly within 5% if the "the weather data were well behaved." Rana et al. (1994) and Steduto et al. (1996) reported that the ASCE-PM type equation under-estimated grass ET in Italy and at several other Mediterranean sites, but Todorovic (1999) found better agreement and attributed the prior under-estimates to a 10% error in solar irradiance. Ventura et al. (1999) evaluated an hourly Penman-type equation and the ICID hourly PM equation (Allen et al., 1994b) indicating that the surface resistance (r_s) factor (70 s m^{-1}) may need to be reduced for hourly daytime calculations, but they used measured R_n and G data.

The purpose of this paper is to compare computed reference grass ET with various methods with the FAO-56 PM equation; to compare daily measured irrigated, mowed fescue grass ET with the FAO-56 PM equation estimates; and to compare measured grass reference ET with alfalfa reference ET both measured simultaneously with weighing lysimeters all in the semi-arid, advective climate of the Southern High Plains.

METHODS AND MATERIALS

This study was conducted at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas (lat. 35°11' N; long. 102°06'; 1170 m elevation MSL). A weighing lysimeter (Schneider et al., 1998), 1.5 m by 1.5 m and 2.3 m deep containing a monolith of Pullman clay loam (*Torrertic Paleustolls*), was used to measure grass ET. It was situated in a 0.3 ha weather station (fetch from 27 to 37 m in the predominate wind direction). Dusek et al. (1987) provide additional details about the weather station, but the station plot area was expanded when the lysimeter was installed in 1994. The station siting is not ideal, and the fetch for standard weather measurements at 2 m is marginal. But this is typical for many agricultural weather stations, and far above average for many research weather stations sites. For comparison, Steduto et al. (1996) reported even smaller sites (although the one in Morocco was 0.7 ha), and the Kimberly, ID, weather station was reported as 0.16 ha (45 m by 36 m) by Wright (1988). Heilman and Brittin (1989) reported significant boundary-layer adjustment occurred within the first 15 m over a smooth Bermuda grass [*Cynodon dactylon* (L.) Pers.] surface as it transitioned from a rougher cotton (*Gossypium hirsutum* L.) field, especially when the Bowen ratio was small as would be expected for the case of an irrigated grass in our situation. The weather station is surrounded by irrigated crops with 8 ha of irrigated alfalfa immediately to the west and south (the predominate wind direction), and rotations of irrigated soybean (*Glycine max* (L.) Merr.) and corn (*Zea mays* L.) in a 0.6 ha microirrigated set of plots to the south and in a 5.7 ha center pivot

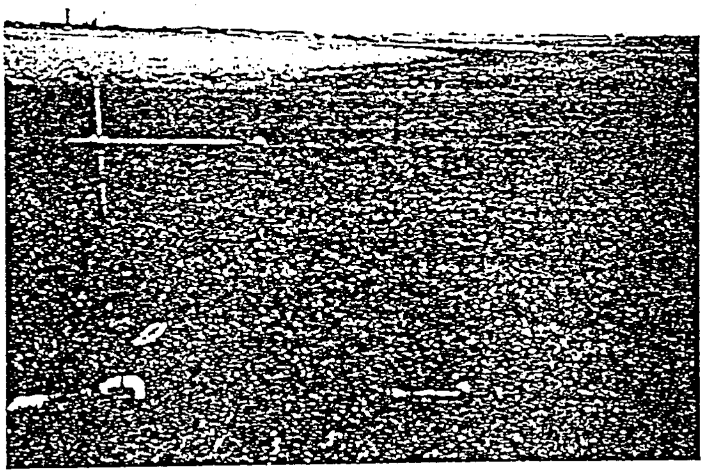

Figure 1. View of the grass lysimeter (directly under the net radiometer) looking to the east (photo taken on Oct. 10, 1997). The outline of the lysimeter is faintly discernable, the white PVC conduit fitting in the lower left of the photo is near the northwest corner of the lysimeter, and the gray material (duct tape) patch on the rubber rain seal is visible in the lower right (on the southwest corner).

plot area to the north and east during this study period. We are convinced that the measured ET rates are valid even with the small fetch, but it is quite possible that the 2-m wind speeds and perhaps the 1.5-m temperatures have, on occasion, been outside the surface boundary layer.

Table 1. Instruments used in the study.

Instrument	Manufacturer	Deployment
Lysimeter scale	Weigh-Tronic	-2.5 m
Pyranometer	Eppley PSP	2 m
Anemometer	Met One 014A	2 m
Temp./RH	Rotronics MP100	1.5 m in CB[1/] shelter
Rainfall	Sierra Misco 2500E	
Barometric pressure	YSI 2014	1 m in CB shelter
Net radiometer	REBS Q*7	1 m
Soil heat flux plates	REBS HFT-1	-50 mm
Soil thermometer	Cu-Co Thermocouples	10 and 40 mm
Data logger	Campbell CR-7X	

[1/] CB is Cotton Belt.

Tall fescue grass was commercially hydro-mulched in the late fall of 1994 on the weather station plot after the lysimeter and subsurface drip irrigation system installation was completed. The seed was a turf blend named Emerald III (Sharp Bros. Seed Co.), which consisted of equal fractions of three tall fescue varieties – Jaguar II, Mustang, and Rebel II. The grass did not emerge as quickly in the fall of 1994 as we had hoped. Consequently, it did not reach full cover with vigorous growth until mid spring in 1995. We are only reporting and using data measured after June 23, 1995, (DOY 174) through December of 1999. Figure 1 shows the lysimeter with a view to the east (the shortest fetch side), and Fig. 2 shows a detail view of the grass in 1997 illustrating excellent growth inside and outside the lysimeter. The grass was mowed regularly with a rotary mower, and the clippings were bagged and removed. The grass height was 0.10-0.11 m after mowing and varied from 0.14 to 0.20 m before mowing. Typically the tallest height was just before the first spring mowing, and then the mowing height was lower (about 0.05 to 0.07 m) to remove dead vegetation from the winter. During peak growth periods, the grass was mowed as frequently as every four to five days.

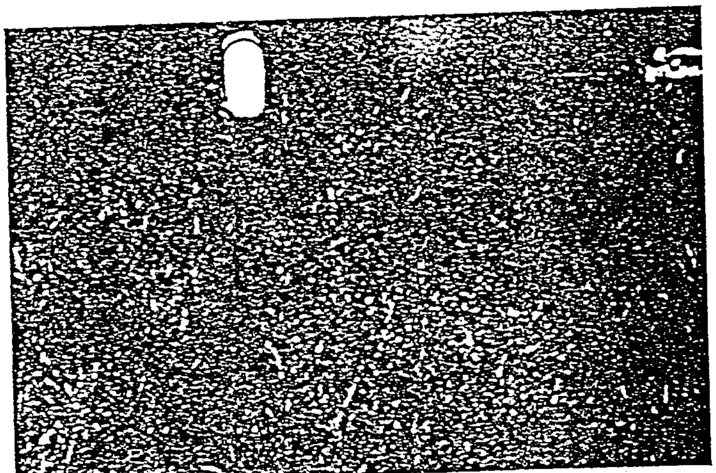

Figure 2. Closeup view of the northwest lysimeter corner (photo taken on Oct. 15, 1997, same day as Fig. 1) showing minimum overlap of the grass blades in or out of the lysimeter. The total wall thickness (both walls and the air gap) is approximately 30 mm.

Table 1 lists the instruments used to measure the various parameters. All sensors were measured at 6 s intervals and averaged for 30-min. and daily (24-h) time periods with a Campbell Scientific CR-7X data logger powered by 120 VAC. The lysimeter used a commercial deck scale with four load beams. The load beams were excited and measured by the same data logger used in the weather station. The lysimeter full-range precision is at least as good as ± 0.1 mm (Schneider et al., 1998), and we believe that short-term (hourly) precision may approach 0.05 mm. The lysimeter air gap between the inner and outer walls was only 10 mm, but when the wall thickness was added, the "mid-wall" lysimeter area would be almost 8% larger than the lysimeter inside area. Typically, we have adjusted the measured ET for our larger lysimeters (for taller crops) to this mid-wall area (Howell et al., 1997). But this lysimeter has a freeboard wall height of 0.10-

0.11 m and an additional effective height of 10 mm for the rubber rain seal. This is about the same height as the mowed grass, and few blades were observed to lap in or to lap over the inside lysimeter wall (Fig. 2). Therefore, we decided not to correct the measured lysimeter mass values to the mid-wall area for grass in this case.

The grass lysimeter net radiometer (a REBS Q*7) was corrected to match the net radiation measured using a REBS Q*5.5 net radiometer that our team more routinely uses. The correction equation that we used was $RnQ_{5.5} = RnQ_7*1.164 + 0.131$. Soil heat flux (REBS HFT-1) was measured with four plates buried at 0.05 m and corrected to the soil surface using soil temperature measured at 0.01 and 0.04 m by four pairs of thermocouples.
The alfalfa ET data for matching days in 1998 and 1999 were obtained with two weighing lysimeter in adjacent 4.2 ha fields (Evett et al., 1998). Only days with alfalfa heights greater than 0.5 m were used for this comparison and without any rain, irrigation, drainage, or maintenance events to disturb the data resulting in 50 days of matched measurements.

The irrigation system used for the grass weather station plot was 1.9 L h^{-1} Geoflow turbulent flow emitters spaced every 0.46 m along the lateral, and the laterals were spaced 0.46 m apart in the weather station plot. The emitters were in 14 mm ID laterals and located 0.15 m deep. The lysimeter had a dense network of 3.8 L h^{-1} emitters (64 arranged in a 0.19-m square grid) that permitted 25 mm of water to be applied in 15 min. Fertilizers (both N and P) were applied through the irrigation water. The irrigations were applied regularly to maintain vigorous grass growth.

Daily reference ET_o was computed with the FAO-56 PM equation (Allen et al.,1998) given in Eq. 3, and all parameters were computed with the equations contained therein. The daily input data included the date, day of year, maximum air temperature, minimum air temperature, mean daily dew point temperature (Howell and Dusek, 1995), mean 2-m wind speed, daily solar irradiance, mean daily barometric pressure, and daily precipitation. The lysimeter ET data included ET, net radiation, soil heat flux density, daily lysimeter drainage (from manual recordings of pumping volumes), and daily lysimeter irrigation amounts. ET data were screened to use only days without mowing, without appreciable rainfall (less than 1 mm), without drainage, and without irrigation. Usually, mowing and many of the irrigation and drainage days coincided. Winter days with snow and/or suspicions of drifting snow were also removed. Mean ambient vapor pressure, e_a, was computed from the mean daily dew point temperature. Daily saturation vapor pressure was computed as the mean saturation vapor pressure at the maximum and minimum air temperatures. The assumed net radiation constants (see Allen et al., 1998 for details) were

G_{sc}	118.1 MJ m^{-2} d^{-1} (solar constant)	a_l	0.34
a_c	1.35	b_l	-0.14
b_c	-0.35	R_{so}	$= (0.75 + 2E\text{-}5*1170)*R_a$, where R_{so} is clear day solar radiation and R_a is extraterrestrial radiation and the 1170 represents the elevation in m at Bushland.
α	0.23 (albedo)		

Daily soil heat flux, G, was assumed to be zero (Allen et al. ,1998) that best fit the measured daily data at Bushland (data not presented). The aerodynamic resistance, r_a, was estimated using the procedures from Allen et al. (1994b) for reference grass for the ASCE-PM equation with these parameters:

h_c	0.12 m	z_{oh}	$= 0.0123\ h_c$
d	$= 2\ h_c / 3$	z_m	2 m
z_{om}	= 0.123 hc	z_h	1.5 m

The surface canopy resistance was assumed to be 70 s m^{-1} (Allen et al., 1994b) for the ASCE-PM and the FAO-56 PM equations. Mean daily barometric pressure was a constant (88.2 kPa) based on elevation (Allen et al., 1994b), and λ was allowed to vary with temperature in the ASCE-PM equation.

Several "potential ET" and "reference ET" equations were used to compute ET with the same 1,653 days of weather data for comparison purposes. Exact equations are found in Howell et al. (1997), but we substituted the Hargreaves and Samani (1985) equation that used daily solar extraterrestrial irradiance and daily maximum and minimum air temperatures in place of the Jensen-Haise equation used in that previous study. The Penman wind functions and matching saturation vapor pressure methods are outlined by Howell et al. (1997) and found in Table 6.2 in Jensen et al. (1990). For discussion, we named these the ASCE-PM ET_o (Jensen et al., 1990 and Allen et al., 1994b), Pen-48 (Penman, 1948; Penman, 1963), FAO-24 (Doorenbos and Pruitt, 1977), P-T (Priestley and Taylor, 1972), and the H-S (Hargreaves and Samani, 1985). All these equations were intended to represent irrigated cool-season grass, except the P-T which has been applied to any crop in "non advective" conditions (a category that does not describe the Bushland environment). The P-T equation is widely used as a measure of the "equilibrium ET" and has interest for other reasons. In addition, the Wright (1996) Penman equation (named Kim-96) was used for grass ET along with the SCS-PM (Martin and Gilley, 1993). Alfalfa reference ET equations included for comparison were the Kim-82 Kimberly-Penman (Wright, 1982) and the ASCE-PM ET_r for alfalfa ($r_s = 45$ s m^{-1}). The same net radiation algorithms were used in all equations except the Kimberly grass and alfalfa equations (Wright, 1982 and 1996) and the SCS-PM (Martin and Gilley, 1993).

All data were analyzed with routine statistical linear regressions and parametric statistics using SigmaStat v2.03 (SPSS Inc., Chicago, IL). All computations were preformed in a spreadsheet program and independently verified with REF-ET (Allen, 1999).

RESULTS AND DISCUSSION

The grass was seeded late in 1994 and did not establish a vigorous stand until the spring of 1995. By mid-May it was growing actively and had reached complete cover. Data collection was started and data quality appeared satisfactory after 23 June (DOY 174) in 1995. Some problems were noticed in the plot that included incomplete wetting across the drip lines and a rust (*Puccinia* spp.) infestation in the 1995 fall. The rust was treated with a fungicide [Tilt (Ciba), a.i. Propiconazole: 1-[[2-(2,4-dichloronphenyl)-4-propyl-1,3-dioxoloian-2-yl]methyl]-1*H*-1,2,4-triazole] applied at 58 μL (a.i.) m^{-2} that effectively eliminated the problem. Plant pathogens have been shown to reduce water uptake in grass (Nus and Hodges, 1986), but we felt this infestation did not significantly change the water use patterns. Some over-watering was needed to fully wet all the areas between the lines in all years. But the grass grew well and maintained excellent quality from 1995 to date. Figures 1&2 illustrate the excellent grass condition.

In early April of 1997, a lightning strike damaged one of the load beams in the scale. The enclosure top had to be removed to provide access to lift and remove the soil monolith and scale for repairs. About 0.6 to 0.8 m of grass sod immediately surrounding the lysimeter was removed during this process as well as the grass sod on the lysimeter so instruments (soil heat flux plates, thermocouples, etc.) could be replaced. A large crane that could span the distance from the east field edge (see Fig. 1) was used to lift the soil container and scale to avoid damaging the grass plot and irrigation system. The scale was repaired and reinstalled within three days with the same crane. Grass sod was cut from the plot edges to replace the sod on and around the lysimeter. The lysimeter was recalibrated and functioning again by early May, but grass growth had not fully recovered until early June, so that the data could be reliably used.

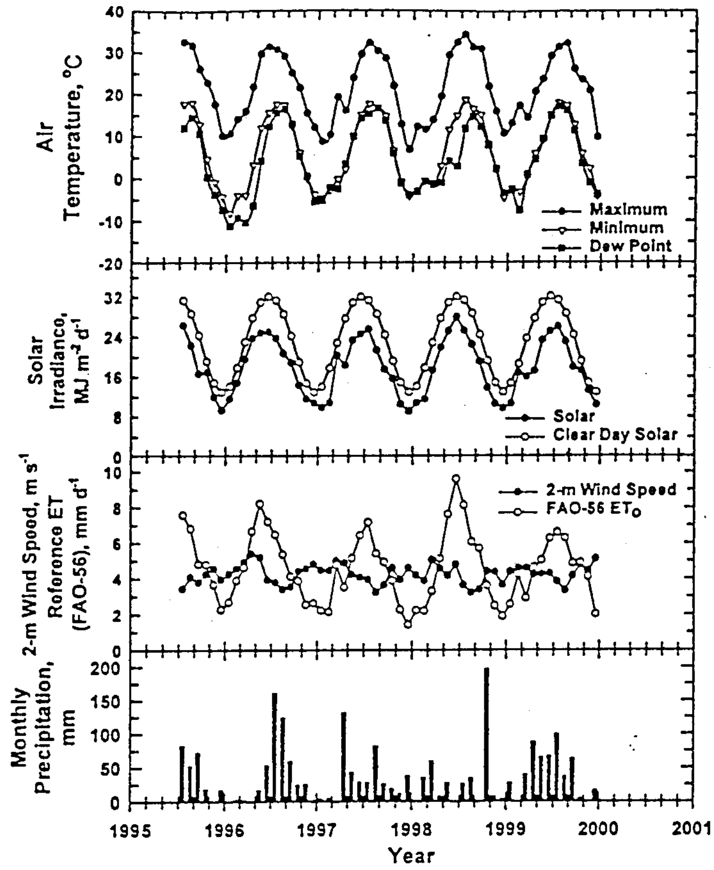

Figure 3. Monthly mean air temperatures and dew point temperature (top graph); solar irradiance and clear day solar irradiance (second graph); 2-m wind speeds and reference ET_o (third graph); and precipitation (bottom graph) for Bushland, TX during the study period.

Environmental conditions during the data collection period (mid 1995 through 1999) were typical for the Southern High Plains. Figure 3 shows the monthly means of selected climatic data during the study, and Table 2 provides a climatic statistical summary for this period. The period included two significant droughts in late 1996 and spring of 1997 and the spring and summer of 1998. Advected energy likely occurred during these periods as evidenced by the greater difference between the dew point and minimum air temperatures (upper graph in Fig. 3). Few "clear" days occur at Bushland, except during the spring (second graph in Fig. 3), and the region has a large mean wind speed, especially during the spring, that couples with the low humidity to result in a large evaporative potential (see FAO-56 PM ET_o in third graph in Fig. 3). The rainfall climate is semi-arid and continental with most of the seasonal rains during the summer months (bottom graph in Fig. 3). All weather data are screened for quality with procedures similar to Allen (1996). Practically all measurements are duplicated either within the weather station or on adjoining larger lysimeter fields. Figure 3 indicates that mean dew point was about 3-4°C lower than T_{min} occasionally. The monthly mean precipitation/ET_o ratio seldom approaches a value of 1.0, and routinely it is below 0.5. The aridity pattern at Bushland based on Fig. 3, appears quite similar to that in Allen (1996) for Kimberly, ID. But, we do not think that Kimberly, ID, experiences the extreme advective spring events with the frequency or extent they occur at Bushland, TX. The two counties in the prevailing wind direction from Bushland have more than 94,000 ha of irrigated land, but like most of the Southern High Plains the irrigated land is dispersed amongst dryland fields and rangelands that are not irrigated.

Reference ET Equation Comparisons

Table 3 presents a summary of the linear regression results comparing the various reference ET methods with the FAO-56 PM reference ET method for the measured Bushland climatic data. It is clear that the Pen-48 equation performs similar to the FAO-56 PM in this extreme environment. Its mean daily computed ratio is almost identical to that for the ASCE-PM equation from which the FAO-56 PM equation was derived. The regression slope for Pen-48 is less than the ideal of 1.0 because it has a slight positive intercept bias (0.202 mm d^{-1}). The FAO-24 Penman equation overestimated grass reference ET by the newer FAO-56 PM, but this has been widely known (Jensen et al., 1990), and is the reason FAO was interested in revising its reference ET method. In fact, the FAO-24 ET estimate, as shown later, is relatively close to alfalfa ET at Bushland. It also has the highest correlation coefficient (r^2 was 0.97), except for the PM equations, and very likely with the proper correction factors (Doorenbos and Pruitt, 1977) for the Bushland wind and humidity regimes, it would perform as well as the Pen-48 equation. The Kim-96 grass Penman equation closely matched both the FAO-56 PM and ASCE-PM equations, but the SCS-PM equation performed almost as well as the ASCE-PM in matching the FAO-56 PM equation calculations. Recall that the SCS-PM uses the Dong et al. (1992) albedo procedures along with the Wright (1982) long-wave radiation procedures to estimate net radiation. The P-T and H-S methods under-estimated grass reference ET by the FAO-56 PM

Table 2. Summary statistics for monthly climate data at Bushland during the study period.

Parameter	T_{max}	T_{min}	T_{dew}	u_{2g}	Solar Irradiance	Bar. Pressure	Rain	FAO-56 ET_o
	°C			m s^{-1}	MJ m^{-2} d^{-1}	kPa	mm	mm d^{-1}
Mean	21.5	6.3	4.1	4.25	17.8	88.9	38.1	4.63
Maximum	34.3	18.6	17.0	5.39	28.0	89.3	196.8	9.59
Minimum	6.8	-8.2	-11.2	3.23	9.1	88.4	0.0	1.42
St. Dev.	8.0	8.3	8.3	0.52	5.7	0.2	42.7	1.93
St. Error Mean	1.1	1.1	1.1	0.07	0.8	0.0	5.9	0.27

Table 3. Summary of linear regressions between the FAO-56 ET_o (independent variable) and other equation estimates for reference ET for all the climatic data from June 23, 1995 through December 31, 1999 (1,653 days) at Bushland, TX. All parameters are in mm d^{-1}, except the mean ratio, slope, standard error of slope, and the coefficient of determination, r^2.

Parameter	FAO-56 PM	ASCE-PM ET_o	Pen-48	FAO-24	Kim-96	SCS-PM ET_o	Kim-82	ASCE-PM ET_r	P-T	H-S
Mean	4.64	4.73	4.70	5.68	4.62	4.70	6.76	6.73	3.09	3.65
Maximum	14.53	14.93	13.55	17.85	15.21	14.48	21.04	22.91	7.18	8.83
Minimum	0.05	0.03	0.29	0.18	0.13	-0.06	0.17	-0.15	0.34	0.08
St. Dev.	2.54	2.59	2.49	3.02	2.85	2.53	3.50	3.75	2.00	1.99
St. Err. Mean	0.062	0.064	0.061	0.074	0.070	0.062	0.086	0.092	0.049	0.049
Mean Ratio	—	1.019	1.016	1.228	0.987	0.985	1.467	1.456	0.668	0.793
Intercept	—	-0.011	0.202	0.211	-0.397	0.085	0.480	-0.033	0.122	0.379
Slope	—	1.021	0.969	1.178	1.080	0.996	1.354	1.464	0.639	0.704
St. Err. Slope	—	0.000	0.004	0.005	0.008	0.002	0.007	0.005	0.011	0.009
r^2	—	1.000	0.969	0.976	0.924	0.994	0.959	0.978	0.659	0.805
$S_{y/x}$	—	0.034	0.437	0.465	0.788	0.196	0.709	0.563	1.167	0.878

method. Both methods had lower coefficients of determination, had slopes and mean ratios much lower than 1.0, and had lower standard deviations (they did not capture the range of variability as well). The two main alfalfa reference equations (Kim-82 and the ASCE-PM ET_r) agreed well, although the ASCE-PM ET_r had a slightly larger coefficient of determination (r^2) and a smaller standard error of the estimate ($S_{y/x}$) when compared with the FAO-56 PM equation for grass.

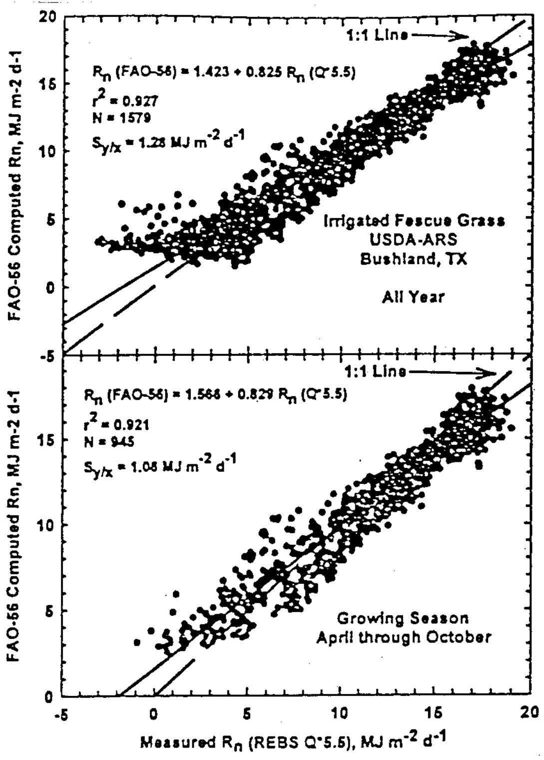

Figure 4. Relationships between measured net radiation and computed net radiation for all year (top) and for the growing season (April through October, bottom) for irrigated fescue grass at Bushland, TX.

Comparison of Measured Net Radiation with FAO-56 PM Computed Values

The corrected measured net radiation (from the REBS Q*7 to a REBS Q*5.5 net radiometer) tracked that computed by the standard methods in FAO-56 PM well, except when the measured daily values were small (less than 1.2 MJ m^{-2} d^{-1}) during the winter (Fig. 4). For these cases, the FAO-56 PM computed R_n remained at about 3 to 4 MJ m^{-2} d^{-1} while the measurements continued to go further negative to -2 to -3 MJ m^{-2} d^{-1}. When only the growing season (April through October) was analyzed, the resulting linear regression was $R_{nFAO\text{-}56\,PM} = 1.57 + 0.83{*}R_{nQ5.5}$, with Sy/x = 1.08 MJ m^{-2} d^{-1} and $r^2 = 0.921$. The agreement is acceptable, and well within the errors possible in measuring R_n. Measured R_n correlations with R_n computed with the Wright (1982) and SCS-PM (Martin and Gilley, 1993) methods were similar. Only the Wright (1982) R_n method for the full year had a slightly better fit to the data (r^2 was 0.93 and $S_{y/x}$ was 1.204 MJ m^{-2} d^{-1}).

Comparison of Measured Grass ET with Computed FAO-56 PM Grass Reference ET

Daily grass ET measured by the lysimeter was compared with the FAO-56 PM reference ETo (Fig. 5) for the extent of this study period. The data set was screened to omit days with rain (greater than 1 mm), mowing, irrigation, or drainage that could introduce water balance uncertainties. Extreme ET and ET_o rates approached 12 mm d^{-1}. Wright (1996) and Allen et al. (1994a) showed few grass ET rates exceeding 9-10 mm d^{-1} for Kimberly, ID, or Davis, CA, respectively. Steduto et al. (1996) and Rana et al. (1994) did not report any measured grass ET rates more than 10 mm d^{-1}, and Todorovic (1999) had one day above 10 mm d^{-1} in southern Italy. The Pen-48 (Penman, 1948) ET_o during the growing season (April through October) was slightly better correlated ($r^2 = 0.73$ and $S_{y/x} = 1.02$ mm d^{-1}) with the measured ET than was the FAO-56 PM ET_o ($r^2 = 0.70$, $S_{y/x} = 1.16$ mm d^{-1}) (Fig. 5). Both linear regressions had slopes near 1.0 if the lines were forced through the origin (slope was 0.992 for FAO-56 PM and 1.002 for Pen-48), but the intercepts were significantly different from zero (P<0.001), so the linear regressions with the intercepts indicate the bias in the estimates. The reference grass ET was slightly better estimated by Pen-48 than FAO-56 PM during the summer months (June through August) (data not shown). Neither equation estimated grass ET during the non-growing season (November through March) well, but this is not surprising since the critical assumptions embodied in the "hypothetical" FAO-56 PM reference grass (α, r_s, and ε) could be incorrect for actual grass during this period. The grass may not be in a condition to transpire at a reference condition although it may still appear "vigorous." In most cases, the fescue grass is dormant and not even green during much of this period at Bushland.

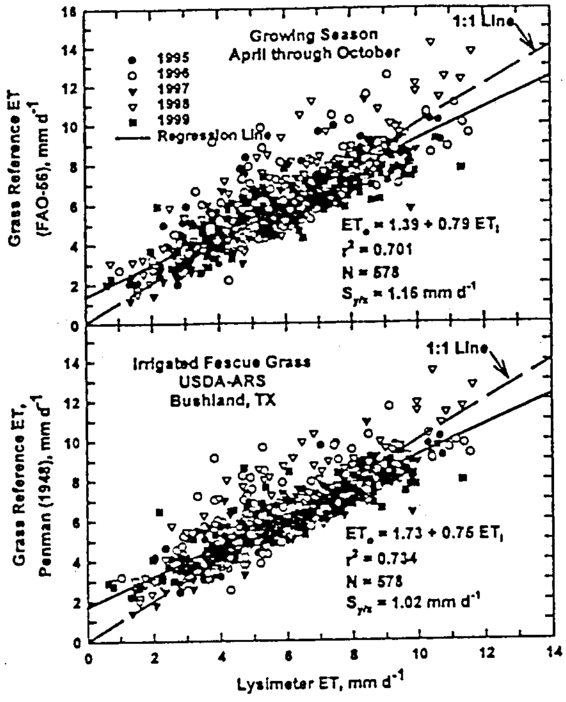

Figure 5. Relationships between computed grass reference ET by the FAO-56 Penman-Monteith equation (top) and the Penman (1948) equation (bottom) to measured irrigated fescue ET.

The overall regression for these data indicated a tendency to over-estimate grass ET for low rates and to underestimate ET for high ET rates by the FAO-56 PM and Pen-48 equations. The $S_{y/x}$ values were similar to that shown by Allen et al. (1994a) for grass at Davis, CA, and that presented for perennial ryegrass (*Lolium perenne* L. 'Barvestra') by Rana et al. (1994) and fescue grass by (Todorovic, 1999). Our scatter was not too unlike that reported by Rana et al. (1994) at Rutigliano, Italy or by Todorovic (1999) at Policoro, Italy. Todorovic (1999) indicated the solar irradiance data used by Steduto et al. (1996) and Rana et al. (1994) were likely at least 10% too low. Todorovic (1999) reported a slightly lower intercept using a constant r_s of 70 s m^{-1} (although still different from 0.0) and a slope of 0.88. He had a slightly better fit using a variable surface resistance.

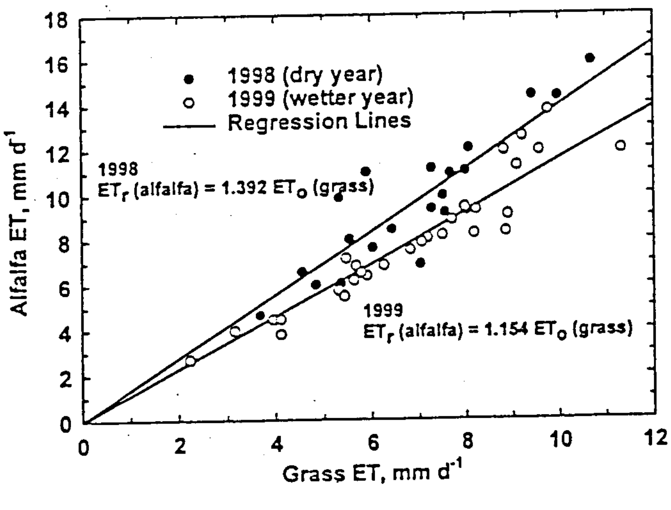

Figure 6. Relationships between measured alfalfa ET and grass ET in 1998 and 1999 on selected days at Bushland, TX.

Comparisons of Measured Grass ET and Alfalfa ET

A data set of 50 days (21 in 1998 and 29 in 1999) with simultaneous lysimeter measurements of alfalfa ET (Evett et al., 1998) and grass ET was analyzed. The 1998 season was drier and warmer than 1999 (Fig. 3) with a mean RH_{min} of 22.0% and 2-m wind speed mean of 4.38 m s^{-1} while in 1999 the mean RH_{min} was 34.9% and 2-m wind speed mean was 4.17 m s^{-1}. The relationship between grass ET and alfalfa ET is shown in Fig. 6, and it clearly indicates the effect of the differing environments. The intercepts for both years were not significantly different from zero, so Fig. 6 only shows the slopes with regressions forced through the origin. Equation 65 in FAO-56 (Allen et al., 1998) would indicate a difference of 0.03 in the slope in Fig. 6 for a 0.5-m tall alfalfa between the two years. The 1999 slope is similar to that reported for Bushland by Evett et al. (1998) for the 1996 and 1997 alfalfa data. These growing seasons had environments similar to the one in 1999 (Fig. 3) while the 1998 season distinctly stands out in Fig. 3 and in Fig. 6 as being more advective. The different slopes in Fig. 6 correspond approximately to the "mean ratios" in Table 3 for the ratio of reference alfalfa ET to reference grass ET (about 1.46 for the Kim-82 and ASCE-PM ET_r) for the 1998 season. The slope for the composite regression (1.253) was similar to the "mean ratio" for the FAO-24 equation (1.228), which was intended for grass. The "adjusted" basal slope for ET_r/ET_o using FAO-56 (Allen et al., 1998) would be 1.23 in 1999 and 1.26 in 1998 for 0.5-m tall alfalfa with the climate corrections. These predicted factors differ less from the measured ratios than those predicted by the reference ET equations themselves.

SUMMARY

ET was measured for an irrigated, mowed fescue grass at Bushland, TX from mid 1995 through 1999. This period included a diverse climate variation typical of the U.S. Southern High Plains. Reference ET was computed using standard weather data with several widely used equations both for grass and alfalfa. All the Penman equations for grass agreed well with FAO-56 PM, except FAO-24, and all the PM equations agreed well with the newer and simplified FAO-56 grass reference equation (Allen et al., 1998). The simpler temperature-radiation equations that are widely used around the world in "non-advective" sites greatly under predicted the estimated grass ET. At Bushland, the Penman (1948) equation estimated grass reference ET as well as the FAO-56 PM equation. The "mean ratios" for the calculated alfalfa reference ET (ET_r) to calculated grass reference ET (ET_o) was about 1.46, which is higher than we expected.

The net radiation formulation in FAO-56 PM represented the measured net radiation acceptably, but there was a noticeable problem during the winter. Net radiation using variable albedo from Wright (1982) or Dong et al. (1992) along with long-wave estimates based on Wright (1982) did not offer a significant improvement nor any degradation.

Actual measured reference grass ET was correlated well with the FAO-56 PM ET_o (Allen et al., 1998), but it was even slightly better represented by the Penman (1948) equation using the FAO-56 R_n and other parameters except for the VPD and the wind function.

Actual measured alfalfa ET in comparison to actual grass ET varied with the environment, but the difference due to advection was greater than that predicted by the FAO-56 correction factor and less than that predicted from the two reference ET equations using Bushland climate data for a typical season; however, it agreed with the mean ratio from the reference ET equations in an advective season.

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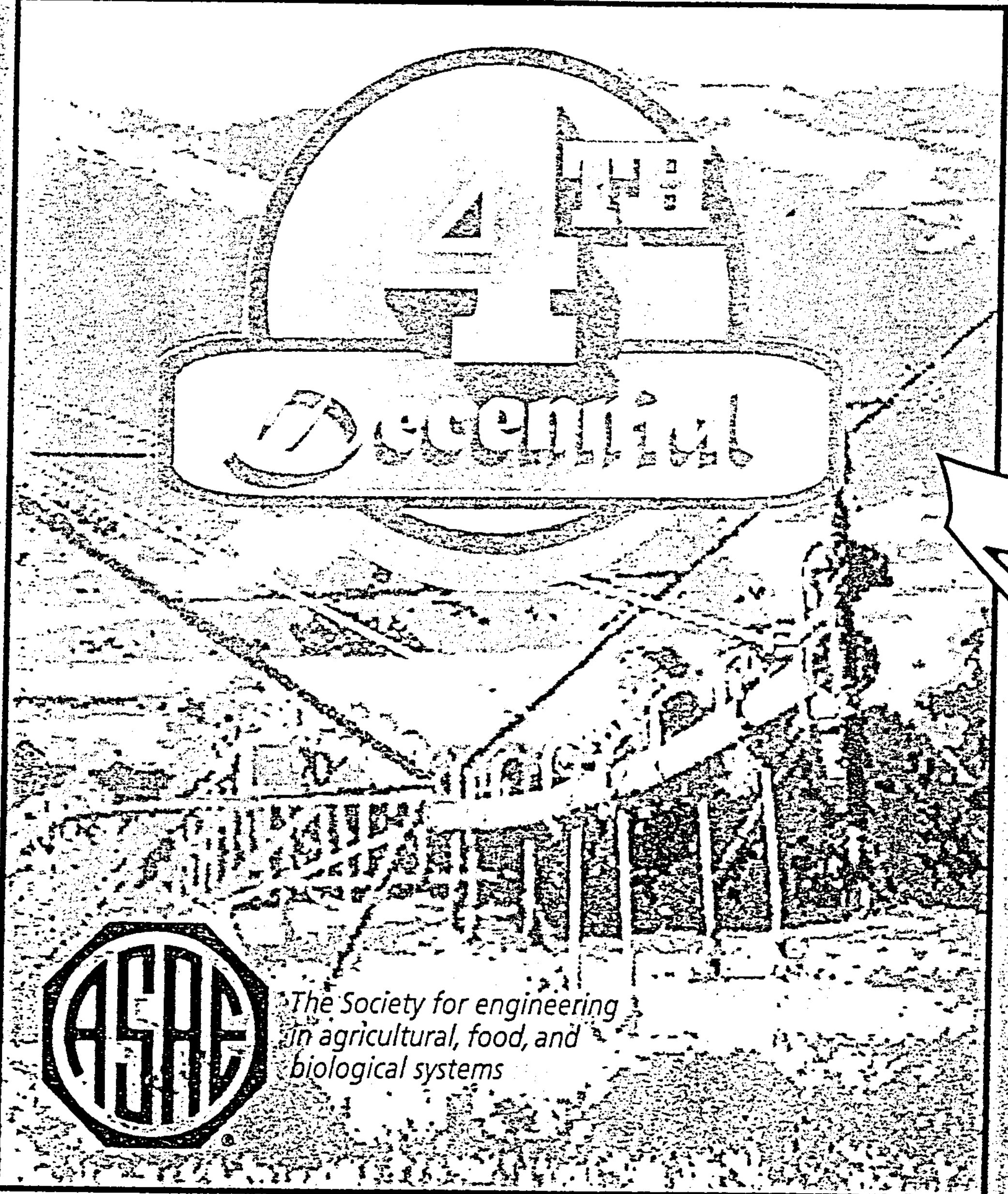

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